Theory of the antiferromagnetic resonance in an intermediate state

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A theory is derived for the antiferromagnetic resonance for an antiferromagnet in an intermediate state. In an intermediate state, the dependence of the resonant frequencies on the external field is strongly affected by the shape of the sample. Experimental results are interpreted.

In an antiferromagnet of finite dimensions the spin-flip transition involves the formation of an intermediate state which is a thermodynamically stable structure of domains of antiferromagnetic and spin-flip phases.[1,2]

Experimental interest in the antiferromagnetic resonance in an intermediate state has recently revived.[3–5] Eremenko *et al.*[3,4] have found that an antiferromagnetic resonance in the intermediate state is excited independently in the antiferromagnetic and spin-flip phases, and the resonant frequencies are independent of the external field. Galkin *et al.*[5,6] have observed a smooth variation of the frequencies of the antiferromagnetic resonance in this region. This seemingly contradictory situation has led us to examine the antiferromagnetic resonance in the intermediate state theoretically.

The application of a uniform alternating magnetic field $h(t)\sim\exp(-i\omega t)$ to a sample gives rise to stimulated nonuniform oscillations of the sublattice magnetization vectors $\mathbf{M}_i(\mathbf{r})$. The effective field acting on the magnetizations $\mathbf{M}_i(\mathbf{r})$ is the resultant of several fields: the composite external field $\mathbf{H}+\mathbf{h}(t)$, short-range fields, the exchange field $\mathbf{H}_e$, the anisotropy field $\mathbf{H}_A$, the Dzyaloshinskiĭ field $\mathbf{H}_D$, and the long-range magnetic-dipole-interaction field $\mathbf{H}_M$.

Far from the point at which the first-order phase transition (the spin-flip transition) terminates, the typical domain dimensions d are far greater than the dimensions of the regions (domain walls) separating the domains. The nonuniformity of the effective field due to short-range forces is important in narrow regions within distances x_0 of domain walls. The static part of $\mathbf{H}_M$ gives rise to an intermediate state. The variable part, $\mathbf{H}_M(t)$, is caused by variable magnetostatic charges at the surface of the sample and at domain walls. These charges give rise to three effects: an additional "hardness" in the spectrum, an inhomogeneous line broadening (due to the irregularity of the domain structure), and a difference between the polarizations of the fields $\mathbf{h}(t)$ and $\mathbf{H}_M(t)$. It can be shown, however, that these effects are small if $H_A \ll H_e$.

It follows that under the condition $x_0 \ll d$ there is essentially no coupling between the oscillations in different domains. The resonant spectrum of an antiferromagnet in an intermediate state therefore consists of the frequencies of the antiferromagnetic resonances of each of the coexisting phases as well as the spectrum of frequencies corresponding to oscillations localized at domain walls. Furthermore, if a periodic stripe domain structure is reached in the intermediate state, there will be the further possibility of the excitation of standing magnetostatic waves with a wavelength $\lambda \sim d$ in the individual domains.

If the susceptibilities of the antiferromagnetic and spin-flip phases, $\chi_{AF}(\omega,H)$ and $\chi_{SF}(\omega,\mathbf{H})$, are much less than unity at resonance, the high-frequency susceptibility tensor of the antiferromagnet in the intermediate state, $\hat{\chi}(\omega,\mathbf{H})$, can be written as follows, where we are ignoring the contribution of magnetostatic waves and of domain-wall oscillations:

$$\hat{\chi}(\omega, \mathbf{H}) = \xi_1 \hat{\chi}_{AF}(\omega, \mathbf{H}_t) + \xi_2 \hat{\chi}_{SF}(\omega, \mathbf{H}_t). \tag{1}$$

This expression takes into account the fact that the strength of the internal field $\mathbf{H}_i$ and also the fractions of the antiferromagnetic phase (ξ_1) and the spin-flip phase ($\xi_2 = 1 - \xi_1$) for a magnetic material in an intermediate state are determined unambiguously by the strength of the external field, and we have $\mathbf{H}_i = \mathbf{H}_t$, where $\mathbf{H}_t$ is the field of the spin-flip transition calculated without allowance for dipole forces.[1] Experimentally, therefore, in a fixed external field $\mathbf{H}$ we should observe a resonance at frequencies corresponding to both the antiferromagnetic and spin-flip phases. The intensities of the resonant signals are proportional to the fractions of the corresponding phases.

How do the resonant frequencies behave when the external field $\mathbf{H}$ is changed? When the magnetic field is rotated in the flipping plane of the sublattice magnetic moments (the XZ plane), on the $H_x H_z$ phase diagram, the line $\mathbf{H} = \mathbf{H}_t$ is described at $H_A \ll H_e$ by the line segment[7] (segment BC in Fig. 1)

$$H_{zt} = H_t = \sqrt{H_A H_e}, \quad |H_{xt}| \leqslant H_x^{(k)} \equiv H_t \psi_k. \tag{2}$$

In an ellipsoidal sample in an intermediate state, the external and internal fields are related by

$$\mathbf{H} = \mathbf{H}_t + 4\pi \hat{N} \{ \xi_1 \mathbf{M}_{AF}(\mathbf{H}_t) + \xi_2 \mathbf{M}_{SF}(\mathbf{H}_t) \}, \tag{3}$$

by virtue of the relation $\mathbf{H}_i = \mathbf{H}_t$, where $\hat{N}$ is the demagnetizing-coefficient tensor, and $\mathbf{M}_{AF}(\mathbf{H}_t)$ and $\mathbf{M}_{SF}(\mathbf{H}_t)$ are the equilibrium magnetizations in the antiferromagnetic and spin-flip phases in the field $\mathbf{H}_t$. Expression (3) maps line segment (2) into an intermediate-state region, which is bounded by an ellipse. Each point of line segment (2) corresponds in the region of the intermediate state to a line segment defined by Eq. (3). Only if the external field changes along these lines does the internal field remain

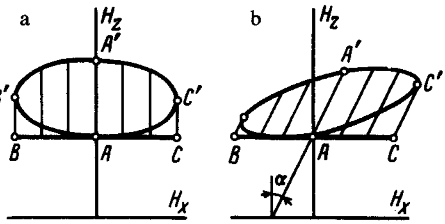

FIG. 1.

constant throughout the region of the intermediate state, so that the resonant frequencies will be independent of H.

To illustrate the results, we consider a plane-parallel plate to which the normal makes an angle α with the easy axis, the Z axis. In this case, the lines of constant internal field are also inclined at an angle α with respect to the Z axis (in Fig. 1, part a corresponds to $\alpha = 0$ and part b to $0<\alpha<\pi/2$). The internal field is H_t as given in (2) and runs parallel to the Z axis on line AA'. The critical points B and C are mapped into the points B' and C', respectively, and we have

$$AA' = 4\pi L \frac{H_t}{H_e} \cos\alpha ; \quad BB' = 4\pi L \frac{H_t}{2H_e} (\cos\alpha - \sin\alpha),$$
$$CC' = 4\pi L \frac{H_t}{2H_e} (\cos\alpha + \sin\alpha) ; \quad L = |\mathbf{M}_1 - \mathbf{M}_2| . \tag{4}$$

It can be seen from Fig. 1a, for $\alpha = 0$, that in the case $\psi_k \ll 1$ a change of the external field along one of the lines $\psi = \text{const}$ $(\tan\psi = H_x/H_z)$ will leave the internal field essentially constant in the region of the intermediate state. This assertion remains in force at $\alpha \neq 0$ (Fig. 1b). For $\alpha \neq 0$, even in a field $\mathbf{H} \| Z$, the change in $\mathbf{H}_i$ as the region of the intermediate state is crossed is

$$\Delta H_z = 0; \quad \Delta H_x = -\frac{2\psi_M(\psi_k + \psi_M \sin^2\alpha)\sin\alpha\cos\alpha}{\psi_k^2 + \psi_M(2\psi_k + \psi_M)\sin^2\alpha} H_x^{(k)}, \tag{5}$$

where $\psi_M = 4\pi L/H_e$. Analysis of this expression reveals that at $\psi_M > \psi_k$ there also exist fields H_z for which the point B' (Fig. 1b) lies to the right of the H_z axis. In this case, no discontinuities at all will be observed in the frequency-field dependence of the antiferromagnetic resonance.

In summary, this analysis shows that the shape of a sample strongly affects the frequency-field dependence of the antiferromagnetic resonance in the region of the intermediate state. Only in Refs. 3 and 4, where thin plates with $\alpha = 0$ were used, were the conditions for independence of the resonant frequencies from the external field met.

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